2.2 High Frequency Wave Generation by Electron Beam Injection in Space

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ABSTRACT

Wave generation by an electron beam in space has been studied in a tethered mother-daughter rocket experiment(CHARGE-2). An electron beam up to 48mA at 1keV was injected from the mother payload and waves generated by the beam were observed by the tethered daughter payload at distances of up to 426 meters. This paper presents four kinds of wave emission in a high frequency range detected in the electron beam experiment and discusses the mechanism of the wave generation.

1. INTRODUCTION

During the tethered rocket experiment(CHARGE-2), electron beams were injected while the tethered payloads were separating. The purposes of the experiment were to study the electrodynamic effects of a space tether and to investigate the beam plasma interaction and spacecraft charging utilizing the tethered payload system. The experiment was conducted as a US-Japan joint space program. Utah State University provided the core instruments for the active experiments and photometers. The Institute of Space and Astronautical Science prepared plasma probes, film cameras, wave receivers, and a tether deployment system. Stanford University provided charge probes, tether biassing and i-v sensors, and University of Michigan a particle energy analyzer. For a description of the instruments and general results, see Raitt et al.[1]. For a description of the results on the electrodynamic effects without beam injection, see Sasaki et al.[2].

2. EXPERIMENTAL

Figure 1 shows the construction of the payload instruments and the pitch angles of the beam injection. The electron gun onboard the mother payload injected an electron beam in perpendicular to the tethered mother/daughter system which lay in a magnetic east-west direction. The hf(0.2-10MHz) wave receiver equipped with a 2.8m-dipole antenna(tip-tip) was onboard the daughter payload. Hf wave signals were analyzed as a frequency spectrum every 250msec with a band width of 200kHz. The measurable range of the receiver

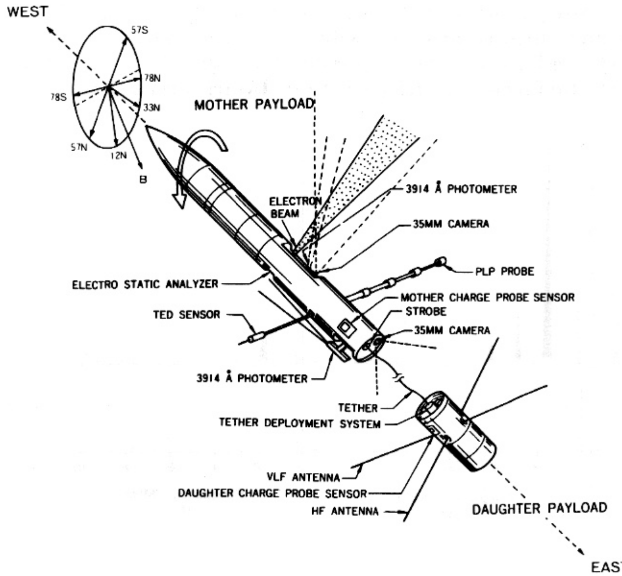

Fig.1 Configuration of CHARGE-2 payload instruments. Pitch angles of the beam injection are also illustrated.

was from 150μV to 5mV in low gain mode and from 5μV to 150μV in high gain mode. The analyzed signal was digitized into 9 bit-words and transmitted to ground. The payload was launched at 00:16:00:420 on 14th December 1985 from White Sands Missile Range, New Mexico, using Black-Brant IV (NASA 36.009UE). It reached an apogee of 262km at 252sec. At 68.0sec, the rocket was despun and then oriented in a magnetic east-west direction. At 115.8sec(161km), the preprogrammed sequence of the active experiment started. 9 active sequences were executed during the flight. The daughter payload was separated into the east direction at 141.9sec(193km) with an initial velocity of 1.05m/sec. Both payloads were connected with an insulated conductive wire until the separation reached 426m at 442sec(118km downleg). A rate control system onboard the daughter payload was intermittently operated to keep the separation velocity. During the separation, the mother payload was rolled by an attitude control system so that the electron beam was injected at different pitch angles with respect to the geomagnetic field in 45 degree increment. The electron beam at 1kV was injected in DC mode up to 31mA in the first half of each programmed sequence and in pulsed mode with current up to 48mA in the latter half.

3. RESULTS AND DISCUSSION

Four kinds of wave emissions were observed, discrete emissions near the electron cycltron harmonics and near the upper hybrid frequency, a broadband emission extending beyond the electron cycltron frequency, and a broadband emission in the whistler wave region (several hundreds of kHz). The typical wave spectrum for each type of emission is shown in Fig.2. The background wave spectrum (just before or after the beam emission) is also shown

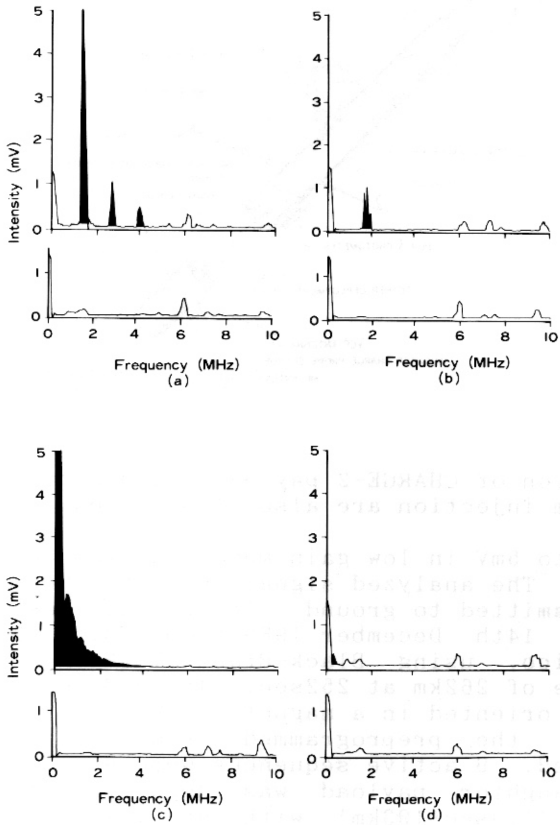

Fig.2 Typical examples of wave spectrum during beam injection (upper panel), together with background spectrum(lower panel). They are from the low gain channel.

below each panel for comparison. Shaded spectra are resulted from the beam injection. The papameters varied in the experiment were the beam current (1-31mA), pitch angle (12, 33, 57, 78 degrees), altitude (120-262km; background plasma density 5×10^2-1×10^5/cc), and the distance between the two payloads (0-426m). The beam current and background plasma density were the major factors which dominate the type of wave emission. The dependence of the pitch angle was not evident if any. Figure 3 shows the parameter region (beam current in x-axis and background plasma density in y-axis) for each type of wave emission. The discrete emission near the upper hybrid frequency was detected only when the beam current was relatively low (less than 5mA). The emissions near the electron cyclotron harmonics were not detected after the

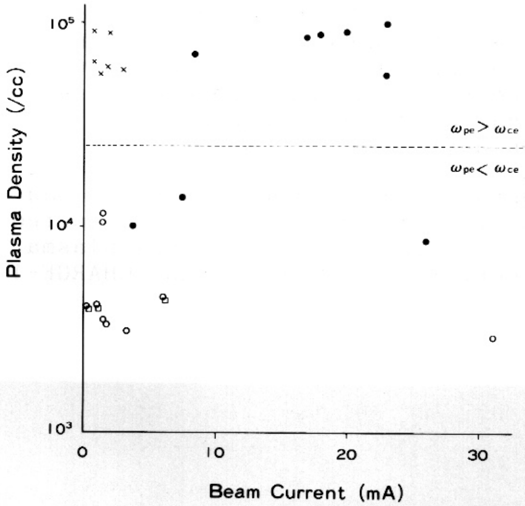

Fig.3 Parameter region for each type of wave spectrum;
X at upper hybrid frequency
○ in the whistler region
□ at cyclotron harmonics
● broadband emission extending beyond the cyclotron frequency

mother/daughter separation, which indicates that this type of emission did not propagate away. Up to 4th harmonics were detected in high gain channel. The discrete emission near the upper hybrid frequency was excited in the region of high plasma density($\omega_{pe} > \omega_{ce}$) and was detected as far as 270m. The broadband emission extending beyond the electron cyclotron frequency was also excited in the region of comparatively high plasma density and was detected as far as 340m. The broadband emission in the whistler wave region was excited in the region of low plasma density($\omega_{pe} < \omega_{ce}$) and was detected even at the final stage (distance 426 m). Since we did not measure the magnetic component of the wave emissions, it is very difficult to identify the wave mode decisively. However, the configuration in which the wave receiver was separated in the direction perpendicular to the magnetic field and to the beam propagation suggests the observed waves must have been more electrostatic rather than electromagnetic. In the electron beam experiments on Spacelab-2 [3] and by NVB-06 rocket [4], they detected a whistler-mode emission with a magnetic component by free-flying wave receivers, but it was measured near the magnetic conjunction (nearly parallel propagation). Both the wave emissions near the upper hybrid frequency and in the whistler region are likely explained by the Landau-type interaction between electrostatic waves and the electron beam. According to the linear theory by Christiansen et al.[5], the largest growth rate of the electrostatic waves occurs on the upper hybrid branch when $\omega_{pe} > \omega_{ce}$ and on the plasma branch when $\omega_{pe} < \omega_{ce}$. These types of emission were also observed in the ECHO-1 electron beam experiment [6]. Although

ECHO-1 was carried out under the condition of $\omega_{pe} < \omega_{ce}$, the plasma radiation near the upper hybrid frequency increased as the density of the background plasma increased while the radiation less than the electron cyclotron frequency ("whistler mode" in their paper) decreased as the plasma density. The wave emission near the cyclotron harmonics is possibly related to the cyclotron coupling with a large k in the beam-hot plasma system, which does not propagate long distance. The broad band emission extending beyond cyclotron frequency was detected when the high current beam was injected in a high dense plasma. This type of emission was observed in NVB-06 [4] and CHARGE-1 [7] when the

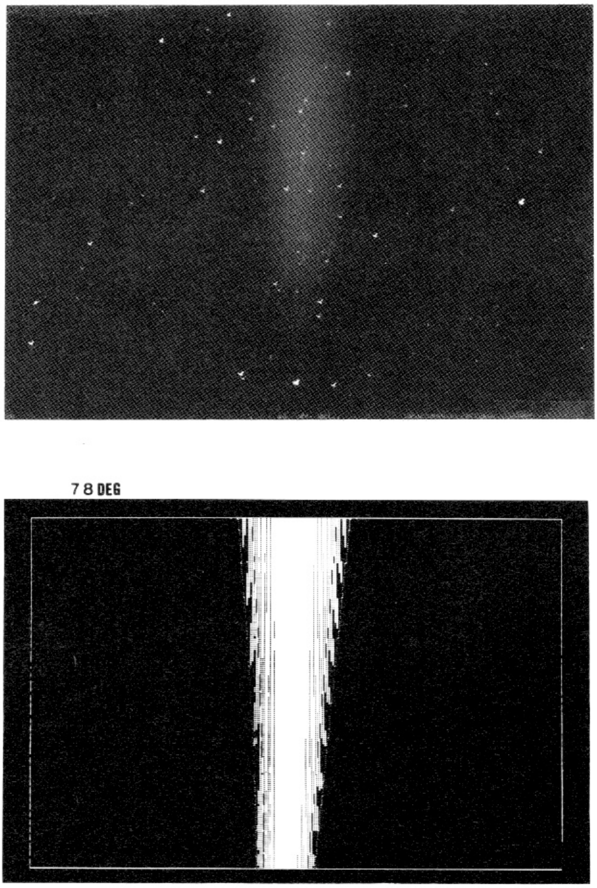

Fig.4 Beam appearance observed by the film camera(upper panel). Lower panel is a result of model calculation based on a single particle motion of electrons in a magnetic field without any scattering effect.

beam current was sufficiently large. Very similar emission with the featureless spectrum has been reported in the laboratory BPD (Beam Plasma Discharge) experiments [8,9]. It is observed when the beam current exceeds a certain threshold level. The generation of the broadband emission suggests that the beam-plasma interaction entered into a non-linear region in which the linear processes are saturated and an equilibrium turbulence is achieved. In the laboratory experiments, the broadband emission is usually accompanied with a scattering of the electron beam and with an abrupt energy transfer to the waves from the electron beam [9], resulting in an rf discharge (BPD). However, in the CHARGE-2 experiment, no evidence for the beam scattering nor discharge was observed by the film camera which monitored the beam trajectory from the rocket skin up to 1.5 m. Figure 4 shows that the beam appearance (upper panel) is almost the same as a model calculation (lower panel) in which the beam electrons are presumed to be propagating without any scattering (effects of the geomagnetic field and defocusing of the lens system are considered in the calculation). This indicates that the beam-plasma interaction with the featureless spectrum in space did not enter a stronger stage of the beam plasma discharge, different from the laboratory BPD experiments.

4. CONCLUSION

The wave generation by an electron beam in space was studied by a tethered diagnostic package which was separated in perpendicular to the magnetic field. Four types of wave emission were detected depending on the background plasma density and beam current. The emissions near the upper hybrid frequency, in the whistler wave region, and near the cyclotron harmonics are believed to be generated by the electrostatic instabilities, and the broadband emission extending beyond the electron cyclotron frequency to be attributed to a strong coupling between the beam and waves in a non-linear region.

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